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**Application of the modified feed formulation to optimize economic and
environmental criteria in beef cattle fattening systems with food
by-products**

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Abstract A simplified ration optimization method was applied to a beef cattle fattening system to evaluate the utilization of food by-products under various situations. The method was extended to reduce feed costs (i.e., economic factors) and nitrogen and phosphorus excretions (i.e., environmental factors) by introducing penalty coefficients of nitrogen and phosphorus contents in each ingredient of the diet in the objective function in traditional linear programming. Six regional food by-products, five commercial concentrates and two roughages were used as ingredients of the fermented total mixed ration. Constraints for the feed formulation were based mainly on nutrient requirements in the Japanese Feeding Standard for Beef Cattle. The replacement price (or acquisition cost) of food by-products was defined as the maximum price of food by-products when the feed cost with the use of food by-products was below the cost with the use of conventional concentrates. The results showed that although the replacement prices were not greatly affected by the penalty levels, they were associated with the changes in the substitution rate of food by-products for concentrates and the price of concentrates. The replacement prices were about 16 (yen/kg, as-fed basis) against the present price level of concentrates, when food by-products were substituted for a half of concentrates. Feed compositions were altered and nitrogen and phosphorus excretions were decreased by the changes of penalties, in spite of the small change in the replacement price of food by-products. Both nitrogen and phosphorus penalties greatly reduced the nitrogen and phosphorus excretions, indicating that nitrogen and phosphorus penalty coefficients should be introduced together in the

1 objective function in order to reduce both excretions efficiently.

2 **Keywords:** beef cattle; excretion; feed formulation; food by-products;

3 nitrogen and phosphorus penalties

4 **Abbreviations:** ADF, acid detergent fiber; CP, crude protein; DIP,

5 degradable intake protein; DM, dry matter; EE, ether extract; MINAS,

6 Mineral Accounting System; NDF, neutral detergent fiber; RR, ratio of

7 roughage to the total feed amount on a DM basis; TDN, total digestible

8 nutrients; TMR, total mixed ration; VA, vitamin A

9

1. Introduction

Due to economic and environmental concerns, the feasibility of using by-products as animal feeds has been examined in many regions of both developing and developed countries. In developing countries, better utilization of non-conventional feed resources (food by-products) which do not compete with human nutrition is imperative in order to meet the projected high demand of livestock products (Maghsoud et al., 2008). In developed countries, low-cost waste management programs that involve feeding by-products from crop- and food- processing industries to farm animals have become very important in recent years (Bampidis and Robinson, 2006). As in Japan, utilization of food by-products has been strongly promoted for raising the self-sufficiency rate of feeds (Sugiura et al., 2009).

Available food by-products, or so-called Ecofeed (Economical and ecological feed resources) in Japan, include beverage wastes such as brewer's grain, distiller's grain, fruit juice pomace and tea waste, food manufacturing wastes such as soybean curd residue (tofu waste), soy sauce cake and blackstrap molasses, vegetable wastes, bakery and noodle wastes and disposals from food service industries. These food by-products usually have high energy and/or protein contents, which can provide competitive alternatives to more traditional energy or protein sources (Westendorf, 2000). Replacing imported commercial feeds with food by-products can save energy in transportation and reduce the environmental impact of burning or landfilling food wastes (Cao et al.,

2009). Nonetheless, despite the vast potential of by-products as a constituent of farm animal diets, the degree of usage is dependent on the economic value of the by-products and the market prices of conventional feedstuffs (Harpster, 2000).

In recent years, environmental pollution caused by high levels of animal waste has become one of the major concerns regarding intensive animal production systems in many countries. Excess nitrogen and phosphorus excretion from feces and urine of farm animals can lead to several environmental problems. For instance, nitrogen contributes to environmental pollution in two ways, as ammonia in the air or as nitrate in soil and ground water, and a high level of phosphorus excretion leads to leakage into surface and ground waters (Tamminga, 1992). In particular, N_2O derived from nitrogen in cattle waste contributes to global warming in the process of Japanese beef production systems (Ogino et al. 2004, 2007), and the reduction in nitrogen excretion from beef production is strongly expected to meet the Kyoto Protocol in Japan.

Linear programming is certainly the most popular method for diet formulation (Brokken, 1971; Crabtree, 1982; Kikuhara et al., 2009; Tedeschi et al., 2000; Tozer, 2000). The ordinal linear programming method enables the formulation of least-cost diets that satisfy specific nutrient requirements, but it cannot consider the effects of excess nitrogen and phosphorus contents in the diets on the excretions of these substances into soil and ground water. To solve this problem, Jean dit Bailleul et al. (2001) and Pomar et al. (2007) modified the ordinal least-cost feed formulation to simultaneously minimize feed cost and

excess nitrogen and phosphorus, respectively, and then applied it to the actual formulation of feed for pig production. Hirooka and Oishi (2010) used the same method to minimize feed cost and nitrogen excretion when whole crop rice silage was utilized as a feed for beef cattle feedlot production in Japan.

The objective of this study was, therefore, to evaluate the economic and environmental impact of the use of food by-products as animal feeds on the Japanese beef fattening system by using the modified least-cost feed formulation method.

2. Materials and methods

2.1. Overview of the simulation

It was assumed in this study that the beef fattening system for Japanese Black (Wagyu) steers starts from the purchase of calves with a body weight of 285 kg (initial weight) at calf markets and culminates with slaughter at a final weight of 714 kg. The fattening period was equally divided into three parts: early, middle and late. The daily gain in each period was estimated from the given average daily gain (0.7kg/day) for the whole fattening period using the Gompertz growth curve function with the estimated mature weight (748 kg). Details of the calculation are shown in the Appendix. Daily nutrient requirements were calculated from the estimated daily gain and body weight in accordance with the Japanese Feeding Standard for Beef Cattle (NARO, 2008). The daily nutrients were summed up for each fattening period, and the modified least-cost feed

1 formulation was then conducted for the constraints for nutrient
2 requirements in each period. All simulations were carried out using the
3 subroutine DLPRS (revised simplex method) for linear programming
4 implemented in the IMSL Math/Library (Visual Numerics, Inc., 1994).

6 *2.2. Feed ingredients and constrained conditions*

7 Fig. 1 shows outline of the system of feed formulation with food
8 by-products in this study. Six regional food by-products (brewer's grain
9 (wet), soybean curd residue (wet), soy sauce cake (wet), blackstrap
10 molasses, udon noodle waste and green tea waste), five commercial
11 concentrates (corn, barley, soybean meal, wheat bran and calcium
12 carbonate) and two roughages (hay and rice straw) were used as
13 ingredients of the fermented total mixed ration (TMR) in this study (Table
14 1). Concentrate and roughage ingredients were selected as the standard
15 imported feeds in the Japanese beef fattening system (Ogino et al., 2004),
16 and the chemical composition of feeds was based mainly on the Standard
17 Tables of Feed Composition in Japan (NARO, 2009). One milligram of
18 beta-carotene was converted into 400 IU of vitamin A.

19 Requirements for the following nutrients on an as-fed basis were set as
20 the constraints of the feed formulation: dry matter (DM; kg/period), crude
21 protein (CP; kg/period), total digestible nutrients (TDN; kg/period),
22 neutral detergent fiber (NDF; kg/period), acid detergent fiber (ADF;
23 kg/period), calcium (Ca; kg/period), phosphorus (P; kg/period),
24 degradable intake protein (DIP; kg/period), ether extract (EE; kg/period)
25 and vitamin A (VA; IU/period). Margins of 10% were added to the nutrient

requirements of DM, CP, TDN and DIP for safety based on the Japanese Feeding Standard for Beef Cattle (NARO, 2008). The lower bounds of the feeding amounts for NDF and ADF were set to be 160 and 100 (g/kg, DM basis), respectively. The effectiveness of fiber in food by-products to stimulate chewing activity and ruminal function was set to be 0.4 (40 %) of that of roughages based on the report of Swain and Armentano (1994). In order to avoid the incidence of urolithiasis, the lower and upper bounds of the ratio of Ca to P (Ca/P) were set to be 1.5 and 2, respectively. The upper bound of EE was assumed to be 60 (g/kg, DM basis). The range between the lower and upper bounds of VA in each period was set to be 3000 IU/day, and the lower limits of VA were set to be the value of the VA requirement for the early period but fixed to lower values for the middle and late periods (3000IU/day and 5000IU/day, respectively), because, in Japan, the VA supply in the middle and late fattening periods of beef production is generally restricted in order to generate a high degree of marbling (Oka et al., 1998). The upper bound for the water content of formulated feeds was set to be 650 (g/kg, as fed basis), since this study assumed the feed formulation for fermented TMR without control of moisture content by drying.

In addition to the above constraints for nutrients, some feed supplies were constrained. The ratio of roughage to the total feed amount on a DM basis (RR) was constrained by the following quadratic function estimated from the data of Ogino et al. (2004):

$$RR \geq 1.211 - 0.003459 \times W(t) + 0.000002727 \times W(t)^2$$

where $W(t)$ is the weight of the animal at age t (days). The upper bound

for the ratio of the feeding amount of wheat bran to concentrates was set to 25 (kg/kg) on an as-fed basis. Furthermore, with respect to food by-products, because soy sauce cake was assumed to include 80 (g/kg, as-fed basis) of NaCl, the upper bound for NaCl in the soy sauce cake was set to be 10 (g/kg, DM). The upper bounds for green tea waste and blackstrap molasses were set to be 150 (g/kg, DM basis) and (400g/day, as-fed basis), respectively.

2.3. Feed price

In the base simulation, the prices of imported roughages and concentrates were assumed to be the average prices of the roughages and concentrates from 2000 to 2008 (MAFF, 2006; MAFF, 2010). Because of lack of price information on food by-products, prices of food by-products including the costs of transportation and preservation were assumed to be identical and variable from 1 to 30 (yen/kg, as-fed basis).

2.4. Modified feed formulation method

Since the simulation in this study aimed at reducing not only the feed cost but also the nitrogen and phosphorus excretions, least-cost ration formulations were executed by an optimization method in which the penalties for high nitrogen and/or phosphorus content feeds were included. The method was based on the following modified linear programming formulae:

$$C = \sum (c_i + \beta_N N_i + \beta_P P_i) x_i$$

$$A X \geq, =, \text{ or } \leq B$$

$$\mathbf{X} \geq \mathbf{0},$$

where c_i is the cost of the i th ingredient, β_N and β_P are the weight coefficients representing the assumed costs associated with nitrogen and phosphorus contents, N_i and P_i are the amounts of nitrogen (CP/6.25) and phosphorus in the i th ingredient, x_i is the amount of the i th ingredient in the vector \mathbf{X} and \mathbf{C} is the ingredient mix costs including the environmental costs per unit weight (yen/period). In addition, \mathbf{A} is the coefficient matrix of the system, where each a_{ij} represents the amount of nutrient or constrained value j in the i th ingredient and \mathbf{B} is the vector of nutrient requirements and constraints (Table 2). The method used to calculate the constrained values for each ingredient is shown in the Appendix. The weight constants β_N and β_P are assumed to be the penalty costs for nitrogen and phosphorus excretions in the objective functions. The amount of nitrogen excretion was calculated as the difference between nitrogen intake and retained nitrogen based on the Japanese Feeding Standard for Beef Cattle (NARO, 2008). In a similar fashion, the amount of phosphorus excretion was calculated based on NRC (2000). The penalty costs were used only for reducing excretions and were not included in total feed cost; hence, the total feed cost was calculated as $\sum c_i x_i$.

2.5. Simulated scenarios

One of the aims of this study was to estimate the replacement price of food by-products. In this study, the replacement price of food by-products was defined as the maximum price of food by-products in the case where

the feed cost with the use of food by-products was below the cost without the use of food by-products. The price can be estimated by comparing the least-cost feed formulation results with and without the use of food by-products. Under this approach, the effect of the change in the penalty costs for nitrogen and phosphorus excretions on the simulated result was also examined. In addition, the effects of the change in the substitution rate of food by-products for concentrates (kg/kg, as-fed basis) and the change in prices of concentrates were analyzed.

Table 3 shows the simulation parameters for the base simulation and the alternatives. The weights for nitrogen and phosphorus penalties were assumed to be 2.30 and 3.92 (euro/kg) (276.0 and 470.4 (yen/kg) assuming 120 yen = 1 euro) based on levies for nitrogen and phosphorus excretions by the Mineral Accounting System (MINAS) in the Netherlands (Hanegraaf and den Boer, 2003). Three penalty levels for nitrogen and phosphorus excretions (no penalty; a penalty identical to that in MINAS (penalty x1 condition); and a penalty twice that in MINAS (penalty x2 condition)), three substitution rates of food by-products (0.50 for the base, 0.25 for the low substitution rate and 0.75 for the high substitution rate), and three price levels of concentrates were assumed.

3. Results

3.1. Effects of nitrogen and phosphorus penalties on the replacement price of food by-products

Fig. 2 shows the differences between the total feed costs with and

without the use of food by-products under three nitrogen and phosphorus penalty conditions under various prices of food by-products. The replacement price of food by-products was 17 (yen/kg) under the no penalty and penalty x1 conditions, and 16 (yen/kg) under the penalty x2 condition. This result showed that the effect of penalty levels for nitrogen and phosphorus excretions on the replacement prices of food by-products was relatively small. The differences in total feed costs between the case with and without the use of food by-products decreased linearly with an increase in price of food by-products under all penalty conditions.

3.2. Differences in nitrogen and phosphorus excretions with and without the use of food by-products

The differences in nitrogen and phosphorus excretions with and without the use of food by-products are shown in Fig. 3. Nitrogen excretion was increased by the use of food by-products under all penalty conditions, although the difference in nitrogen excretion decreased with an increase in the penalty levels. In contrast, phosphorus excretion was decreased with the use of food by-products under all penalty conditions and the rate of decrease was increased in keeping with the penalty levels.

3.3. Optimal ration formulation under the three penalty levels

Table 4 shows the simulated results of feed compositions, feed costs and nitrogen and phosphorus excretions for each fattening period under the three penalty conditions. Feed costs in the total fattening period

increased consistently with the penalty levels, but the differences among the three penalty levels were small. However, nitrogen and phosphorus excretions in each period and also in the total fattening period decreased markedly with an increase in the penalty levels. The decreases in nitrogen and phosphorus excretions with increasing penalty levels resulted from the differences between feed compositions under the three penalty levels.

When no penalties were introduced, soybean curd residue was selected as the main feed resource. When the penalty was introduced, however, the composition of food by-products was strongly affected; the proportion of soybean curd residue strongly decreased but that of udon noodle waste increased in keeping with the penalty levels. Brewer's grain was not selected as a food by-product ingredient in the optimal ration under any of the penalty conditions. Green tea waste was selected instead of hay as a resource of VA in the early period, but VA restrictions in the middle and later period were too severe to allow the use of green tea waste and hay as feeds. The composition of concentrates was also affected by the change in the penalty levels; enhanced penalty levels increased the proportions of barley but decreased that of wheat bran.

3.4. Effects of various nitrogen and/or phosphorus penalty levels on feed costs and excretions

The effects of various nitrogen and/or phosphorus penalty levels on feed costs with the use of food by-products are presented in Fig. 4. The feed costs increased consistently with the penalty levels of nitrogen and phosphorus excretions, but the range of the rates of increase was small

(0-2.5%). In contrast, changes in the penalty levels of nitrogen and phosphorus excretions led to large reductions of nitrogen and phosphorus excretions (Fig. 5). It was noteworthy that the introduction of both nitrogen and phosphorus penalties at a high level led to larger reductions of nitrogen and phosphorus excretions compared with the unilateral introduction of nitrogen or phosphorus penalty.

3.5. Influence of the substitution rate of food by-products for concentrates and price levels of concentrates on the replacement price of food by-products

Table 5 shows the replacement price of food by-products under different substitution rates and concentrate prices. The result clearly demonstrates the positive relationship between the replacement price of food by-products and the concentrate price levels and the negative relationship between the replacement price of food by-products and the substitution rates of food by-products for concentrates.

4. Discussion

4.1. Reduction of phosphorus excretion with the use of food by-products

Nitrogen excretion was increased by the use of food by-products because of higher CP contents of food by-products selected in this study than those of concentrates, but phosphorus excretion was strongly decreased with the use of food by-products (Fig. 3). In the ration formulation with only concentrates, the proportion of wheat bran was

1 approximately the upper bound of the feeding limit. Because wheat bran
2 had the highest phosphorus content per DM among all ingredients of the
3 feeds used in this study, the substitution of other food by-products for
4 wheat bran resulted in a reduction of the total phosphorus excretions.
5 This result suggests that the phosphorus excretion in the Japanese beef
6 fattening system may be reduced by the use of local food by-products
7 instead of wheat bran.

8 9 *4.2.Changes in feed ingredients selected by the feed formulation under* 10 *the three penalty levels*

11 The proportion of soybean curd residue was the highest when no
12 penalties were introduced (Table 4). Cao et al. (2009) reported that the
13 addition of dried soybean curd residue to TMR silage increased the
14 fermentation quality and resulted in high nutrient digestibility. Moreover,
15 in a later study, Cao et al., (2010) reported that fermented TMR increased
16 digestibility, decreased methane emissions which might be caused by the
17 conversion of lactic acid to propionic acid in the rumen, and resulted in a
18 lower loss of energy as methane compared to non-fermented TMR. In
19 consideration of this finding as well as the present simulation, the
20 inclusion of soybean curd residue in fermented TMR is a suitable solution
21 both from a nutritional and environmental point of view.

22 However, the proportion of soybean curd residue decreased but that of
23 udon noodle waste increased consistently with the penalty levels. This
24 was attributable to the fact that the udon noodle waste had low CP and
25 high TDN contents while the soybean curd residue had high CP and high

1 TDN contents. However, Maghsoud et al. (2008) reported that noodle
2 waste degraded rapidly because of its high level of starch, and Wang et al.
3 (2009) mentioned that high dietary starch resulted in a decrease in
4 ruminal pH and that subacute ruminal acidosis can occur when the pH
5 decreases dramatically. Adding some constrained parameters associated
6 with ruminal fermentation characteristics in the feed formulation may
7 improve the result of formulation.

8 Brewer's grain has considerable potential as a feed for growing and
9 finishing cattle because of its high energy and high CP and apparent
10 roughage characteristics (Preston et al. 1973). However, brewer's grain
11 was not selected as a food by-product ingredient in the optimal ration.
12 This may have been due to the low TDN content per DM of brewer's grain
13 compared to that of soybean curd residue.

14 In the ingredients of concentrates, the proportion of barley was
15 increased but that of wheat bran was decreased in keeping with the
16 penalty levels. It is known that wheat bran is a generally suitable feed
17 resource for beef cattle because of its degradable fiber content and
18 relatively low price compared to other concentrates. Furthermore, an
19 amount of wheat bran less than that isocaloric to corn may provide a
20 similar production response due to a lessening of the negative associative
21 effects on forage intake and digestibility (Hess et al., 1996).
22 Nevertheless, the introduction of penalties reduced the content of wheat
23 bran in the optimal rations because of its high phosphorus content, and
24 resulted in a switch from wheat bran to barley as an alternative resource
25 of protein and fiber.

4.3. Importance of introducing both nitrogen and phosphorus penalties

In the simulation for a beef cattle production using whole crop rice silage, Hirooka and Oishi (2010) stated that the introduction of a penalty for nitrogen excretion lead to a simultaneous reduction in phosphorus excretion. Jean dit Bailleul et al. (2001) and Pomar et al. (2007) also used the feed formulation method for pig production including only nitrogen penalty or phosphorus penalty. The results of the present study shown in Fig.5, however, indicated that the introduction of both nitrogen and phosphorus penalties could have a synergistic effect on the reduction of nitrogen and phosphorus excretions; in other words, the introduction of the nitrogen penalty did not result in a satisfactory reduction of phosphorus excretion and vice versa.

4.4. Replacement price levels of food by-products associated with the substitution rate of food by-products for concentrates and price levels of concentrates

The replacement price of food by-products was positively related with the concentrate price levels and negatively related with the substitution rates of food by-products for concentrates (Table 5). The positive relationship between the replacement price of food by-products and the concentrate price levels was expected, because the concentrate prices may compete with the food by-product prices, and thereby increases in the former could lead to increases in the latter. Meanwhile, the negative relationship between the replacement price of food by-products and the

1 substitution rates of food by-products for concentrates might indicate
2 that a large quantity of food by-products with high water content should
3 be required to replace the full amount of nutrients in concentrates.

4 The average replacement price of food by-products at all price levels
5 and substitution rates in Table 5 was 17.3 (yen/kg), which was about 37%
6 of the average price of concentrates (46.8 yen/kg). This may be because a
7 high level of food by-products is needed to substitute for concentrates
8 due to their low DM content. Therefore, if the total cost for transport and
9 conservation of food by-products is about 11 (yen/kg) on an as-fed basis
10 in Japan, as reported by Kajikawa (1996), the food by-products should be
11 supplied at a very low price (6.3 yen/kg) from waste managers.
12 Nevertheless, the use of food by-products would be supported by the
13 public because it can help waste managers solve the economic and
14 environmental problems of waste disposal.

16 *4.5. Applicability of the feed formulation method*

17 The optimization of multiple criteria pertaining to feed formulation,
18 such as minimization of feed cost and environmental load, has generally
19 been carried out using multi-objective models (Tozer and Stokes, 2001;
20 Giasson et al., 2002; Castrodeza et al., 2005). However, it is often
21 difficult to find a solution using multi-objective models. In addition,
22 these models are technically complicated, and their use requires specific
23 computation skills or specialized software. In contrast, the least-cost
24 ration formulation method with the introduction of nitrogen and
25 phosphorus penalty coefficients used in the present study represents a

1 simple modification of the traditional linear programming and can be
2 easily and widely applied to various feeding conditions. Numerous
3 by-products, including food, agricultural, and industrial by-products,
4 have potential for use as animal feeds, but their availability varies
5 enormously among regions and their nutritional values also vary
6 depending on the conditions of the local production systems. To account
7 for the regional differences in feed availability, Grasser et al. (1995)
8 formulated rations including different combinations of nine by-products
9 like brewer's grain and citrus pulp for dairy productions in three regions
10 in California. Therefore, the wide availability of the feed formulation
11 method can allow livestock producers to utilize economically and
12 environmentally effective by-products as local feed resources.

14 *4.6. Implication of the use of food by-products as feeds in beef production*

15 At present, by-product feedstuffs constitute a significant portion of the
16 feedstuffs in animal industries and a beneficial resource that can be
17 converted by ruminants into animal products that otherwise would need to
18 be disposed of (Grasser et al., 1995). Agricultural and food by-products
19 could substantially contribute to the feed supply and release the pressures
20 on agricultural land use (Steinfeld et al., 2006). Therefore, by-product
21 feedstuffs are no longer considered food waste by-products but rather
22 normal commodities to be incorporated into a commercial feeding program
23 (Westendorf, 2000). However, it should be noted that some problems still
24 exist in the use of food by-products. One important problem to be solved
25 is the high nutritional variability of food by-products, which is caused by

differences in season, region, processing, etc. Moreover, one concern with the use of food by-products might remain, especially for the beef production system: the beef quality. In fact, a negative relationship between the proportion of by-products in diets and carcass quality of culled animals has been reported (Harpster, 2000; Bampidis and Robinson, 2006; Sugimoto et al., 2009). Therefore, further investigations will be needed to identify measures for improving the quality control of food by-products and the beef produced using them, as well as additional factors that might be constrained in the feed formulations. These investigations will promote economically and environmentally efficient utilization of the food by-products in beef production systems.

5. Conclusions

This study demonstrated the application of the modified least-cost feed formulation to the beef fattening production system using food by-products, while introducing the penalty costs for nitrogen and phosphorus excretions. Analyses of the price of food by-products indicated that the replacement price was not greatly affected by the change in the penalty level. The nitrogen and phosphorus penalties greatly changed the feed composition and reduced the excretions, indicating the importance of introducing both penalty coefficients to the objective function for effective reduction of both excretions in animal productions. These analyses showed the simplicity and efficacy of the modified least-cost feed formulation method for determining

economically and environmentally optimal rations using various feed resources.

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Appendix

1. Estimation of the Gompertz growth curve parameters using average daily gain

The Gompertz growth curve function is expressed as:

$$W_t = Ae^{-Be^{-kt}} \quad (\text{A.1})$$

where W_t (kg) is the body weight at age t (days), the parameter A is mature weight, the parameter B is the constant of integration and the parameter k is the maturing rate. The function (A.1) can be transformed as:

$$-Be^{-kt} = \log(W_t / A). \quad (\text{A.2})$$

When the start days t_s and final days t_f of fattening and the start weight W_s and the final weight W_f are provided, then the following expressions are obtained:

$$-Be^{-kt_s} = \log(W_s / A) \quad (\text{A.3})$$

$$-Be^{-kt_f} = \log(W_f / A). \quad (\text{A.4})$$

Dividing (A.3) by (A.4) and logarithmically transforming both sides leads to the following function (A.5) for solving the parameter k :

$$k = \frac{\log\{\log(W_s / A) / \log(W_f / A)\}}{t_f - t_s}. \quad (\text{A.5})$$

Next, the average daily gain (ADG) for the entire fattening period is determined as:

$$ADG = \frac{W_f - W_s}{t_f - t_s} \quad (\text{A.6})$$

1 and the function (A.5) can be expressed by ADG as:

$$k = \frac{\log\{\log(W_s / A) / \log(W_f / A)\}}{(W_f - W_s) / ADG}. \quad (\text{A.7})$$

2 Thus, we can calculate the parameter k by the expression (A.7) when the
3 parameters A , W_s , W_f and ADG are provided, and we can then
4 calculate the parameter B by the calculated parameter k and the given
5 parameter t_s by the expression (A.3).

6 Finally, the daily gain DG_t (kg) at age t (days) by the Gompertz growth
7 function is expressed using the calculated growth parameter k and the
8 mature weight A as:

$$DG_t = kW_t \log(A / W_t). \quad (\text{A.8})$$

9
10 2. Setting constrained values for restriction of the feeding amount in
11 linear programming

12
13 For example, when the upper bound for the ratio of the feeding amount of
14 wheat bran (B) to concentrates ($B+C$: C is the total feeding amount of
15 other concentrates) is set to be 25%, the relationship between B and C
16 is:

$$B \leq 0.25(B + C). \quad (\text{A.9})$$

17 Therefore, the following inequality constraint is specified and the
18 coefficients become the constrained values shown in Table 2:

$$0.25C - 0.75B \geq 0. \quad (\text{A.10})$$

Table 1Composition of ingredients¹⁾ and the ingredient prices²⁾ used in this study

	DM	CP	TDN	NDF	ADF	Ca	P	DIP	EE	VA	Price
	g/kg, as-fed basis	g/kgDM	g/kgDM	g/kgDM	g/kgDM	g/kgDM	g/kgDM	g/gCP	g/kgDM	IU/kgDM	yen ³⁾ /kg, as-fed basis
Food by-products: Eco											
1 Brewer's grain (wet)	277	249	722	269	97	2.9	6.1	0.594	101	0	variable
2 Soybean curd residue (wet)	225	262	911	135	89	3.8	3.6	0.695	115	0	variable
3 Soy sauce cake (wet)	660	277	791	140	98	4.8	1.6	0.858	166	0	variable
4 Blackstrap molasses	732	131	706	0	0	11.8	1.1	0.930	9	0	variable
5 Udon noodle waste	252	131	810	05	3	0	0.8	0.852	19	0	variable
6 Green tea waste	200	210	465	238	174	8.0	2.5	0.114	186	2510	variable
Purchased concentrates: Con											
1 Calcium carbonate	996	0	0	0	0	388.9	0.1	0	0	0	60.0
2 Corn	855	89	936	36	20	0.3	3.0	0.605	44	2000	40.1 (32.5, 59.2)
3 Barley	885	120	841	227	67	0.6	3.7	0.850	24	0	49.1 (41.0, 73.8)
4 Soybean meal	882	510	871	155	96	3.7	7.2	0.740	22	0	65.3 (56.7, 87.4)
5 Wheat bran	868	181	722	426	141	1.2	11.4	0.822	49	0	32.7 (27.5, 42.9)
Roughages: Rou											
1 Hay ⁴⁾	851	114	617	645	394	4.7	2.8	0.705	34	11000	54.9
2 Rice straw	878	54	428	631	392	3.0	1.3	0.490	21	1200	36.0

¹⁾ National Agriculture and Food Research Organization (2009): DM, CP, TDN, NDF, ADF, CA, P, DIP, EE and VA are total dry matter, crude protein, total digestible nutrients, neutral detergent fiber, acid detergent fiber, calcium, phosphorus, degradable intake protein, ether extract and total vitamin A, respectively.

²⁾ Ministry of Agriculture, Forestry and Fisheries (2006, 2010): the prices of food by-products are variable between 1 and 30, the prices for concentrates and roughages are average values in 9 years (from 2000 to 2009) and the prices in parentheses for concentrates indicate the lowest (left) and the highest (right) prices in the 9 years.

³⁾ 1 euro = 120 yen

⁴⁾ Includes Italian ryegrass hay, timothy hay and orchardgrass hay, based on Ogino et al. (2004).

Table 2

Table representing the coefficient_matrix **A** and the vector of nutrient requirements and constraints **B** for the least-cost feed formulation for the production in which food by-products were used in this study¹⁾

	Eco1	Eco2	Eco3	Eco4	Eco5	Eco6	Con1	Con2	Con3	Con4	Con5	Rou1	Rou2	Constraint ²⁾
Limitation for nutrient requirements														
DM	0.277	0.225	0.660	0.732	0.252	0.200	0.996	0.855	0.885	0.882	0.868	0.851	0.878	= DMReq
CP	0.069	0.059	0.183	0.096	0.033	0.042	0	0.076	0.106	0.450	0.157	0.097	0.047	≥ CPRReq
TDN	0.200	0.205	0.522	0.517	0.204	0.093	0	0.800	0.744	0.768	0.627	0.525	0.376	≥ TDNReq
NDF	0.074	0.030	0.092	0	0.001	0.048	0	0.031	0.201	0.137	0.370	0.549	0.554	≥ 0.16DMReq
ADF	0.027	0.020	0.064	0	0.001	0.035	0	0.017	0.059	0.085	0.122	0.335	0.344	≥ 0.10DMReq
Ca	0.0008	0.0009	0.0032	0.0087	0	0.0016	0.3873	0.0003	0.0005	0.0033	0.0010	0.0040	0.0026	≥ CaReq
P	0.0017	0.0008	0.0011	0.0008	0.0002	0.0005	0.0001	0.0026	0.0033	0.0064	0.0099	0.0024	0.0011	≥ PReq
Ca:P balance (lower limit)	-0.0017	-0.0004	0.0016	0.0075	-0.0003	0.0009	0.3872	-0.0036	-0.0044	-0.0063	-0.0138	0.0004	0.0009	≥ 0 (Ca/P=1.5)
Ca:P balance (upper limit)	-0.0025	-0.0008	0.0011	0.0071	-0.0004	0.0006	0.3871	-0.0049	-0.0060	-0.0094	-0.0187	-0.0007	0.0004	≤ 0 (Ca/P=2.0)
DIP	0.041	0.041	0.157	0.089	0.028	0.005	0	0.046	0.090	0.333	0.129	0.068	0.023	≥ DIPReq
EE	0.028	0.026	0.109	0.001	0.006	0.011	0	0.038	0.021	0.019	0.043	0.025	0.018	≤ 0.06DMReq
VA (lower limit)	0	0	0	0	0	12550	0	2339	0	0	0	12926	1367	≥ VAREq
VA (upper limit)	0	0	0	0	0	12550	0	2339	0	0	0	12926	1367	≤ VAREq+3000
Limitation for amount of feeds														
Roughage	0	0	0	0	0	0	0	0	0	0	0	0.851	0.878	≥ RR
Wheat bran in concentrates	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	-0.75	0	0	≥ 0
Water content	-0.073	-0.125	0.310	0.382	-0.098	-0.150	0.646	0.505	0.535	0.532	0.518	0.501	0.528	≥ 0 (65%water)
Soy sauce cake	0	0	0.08	0	0	0	0	0	0	0	0	0	0	≤ 0.01DMReq
Blackstrap molasses	0	0	0	1	0	0	0	0	0	0	0	0	0	≤ 0.4
Green tea waste	0	0	0	0	0	0.200	0	0	0	0	0	0	0	≤ 0.15DMReq
Substitution rate of food by-products for concentrates	-(1-Sub ³⁾)	-(1-Sub)	-(1-Sub)	-(1-Sub)	-(1-Sub)	-(1-Sub)	Sub	Sub	Sub	Sub	Sub	0	0	≥ 0

¹⁾ Eco1: Brewer's grain (wet), Eco 2: Soybean curd residue (wet), Eco3: Soy sauce cake (wet), Eco 4: Blackstrap molasses, Eco 5: Udon noodle waste, Eco 6: Green tea waste, Con1: Calcium carbonate, Con2: Corn, Con3: Barley, Con 4: Soybean meal, Con5: Wheat bran, Rou1: Hay, Rou2: Rice straw

²⁾ Req, such as "DMReq", indicates nutrition requirement including 10% safety margin and RR means lower boundary of roughage ratio (/kgDM).

³⁾ Sub indicates substitution rate of concentrates for food by-products.

Table 3

Base condition and the alternatives in simulation

Simulation conditions	Base and the alternatives
Nitrogen and phosphorus penalty	
No penalty	0 (Base) ¹⁾
Penalty x1 ²⁾	N: 2.30 euro/kg ³⁾ , P: 3.92 euro/kg
Penalty x2	N: 4.60 euro/kg, P: 7.84 euro/kg
Substitution rate of food by-products for concentrates	
Low	<u>0.25</u>
Middle	<u>0.50 (Base)</u>
High	<u>0.75</u>
Price level of concentrates ⁴⁾ (for Corn, Barley, Soybean meal, Wheat bran)	
Low	32.5, 41.0, 56.7, 27.5 yen ³⁾ /kg
Average	40.1, 49.1, 65.3, 32.7 yen/kg (Base)
High	59.2, 73.8, 87.4, 42.9 yen/kg

¹⁾ Base situation

²⁾ Derived from Hanegraaf and den Boer (2003)

³⁾ 1 euro = 120 yen

⁴⁾ also see Table 1

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Table 4

Optimum rations, feed costs and nitrogen and phosphorus excretions under three penalty conditions, when the price of food by products was set to be 16 (yen¹⁾/kg, as-fed basis)

Penalty ²⁾	Period ³⁾	Feed composition ⁴⁾ (kg/kg in total feed amount, as-fed basis)													Feed cost (yen)	Excretion	
		Eco1	Eco2	Eco3	Eco4	Eco5	Eco6	Con1	Con2	Con3	Con4	Con5	Rou1	Rou2		N (kg)	P (kg)
0	1	0	24.27	7.64	2.79	0	6.24	0.46	32.65	0	0	7.82	0	18.14	87232	32.87	5.11
	2	0	35.50	7.42	2.99	0	0	0.75	14.40	16.78	0	13.98	0	8.18	78422	38.25	7.44
	3	0	33.14	7.63	3.47	1.48	0	0.86	24.69	0	0	20.16	0	8.58	63807	31.65	6.08
	Total	0	30.97	7.56	3.08	0.49	2.08	0.69	23.91	5.59	0	13.99	0	11.63	229460	102.77	18.63
1	1	0	24.27	7.64	2.79	0	6.24	0.46	32.65	0	0	7.82	0	18.14	87228	31.84	4.97
	2	0	4.32	7.54	3.04	30.94	0	0.60	14.63	22.38	0	8.23	0	8.32	79621	32.88	5.91
	3	0	0	7.62	3.47	34.63	0	0.86	24.66	0	0	20.20	0	8.57	63827	30.35	5.92
	Total	0	9.53	7.60	3.10	21.85	2.08	0.64	23.98	7.46	0	12.08	0	11.67	230676	95.07	16.81
2	1	0	24.32	7.86	2.87	0	5.61	0.36	37.95	0	2.17	0.18	0	18.67	87724	31.84	4.12
	2	0	0.16	7.61	3.07	34.40	0	0.49	14.12	26.68	0	3.96	0	9.51	81740	30.43	4.59
	3	0	0	7.80	3.55	33.67	0	0.63	24.58	8.61	0	11.22	0	9.94	65176	27.60	5.15
	Total	0	8.16	7.76	3.16	22.69	1.87	0.49	25.55	11.76	0.72	5.12	0	12.70	234640	89.88	13.86

¹⁾ 1 euro = 120 yen

²⁾ see Table 3

³⁾ 1: Early fattening period, 2: Middle fattening period, 3: Late fattening period

⁴⁾ Eco1: Brewer's grain (wet), Eco 2: Soybean curd residue (wet), Eco3: Soy sauce cake (wet), Eco 4: Blackstrap molasses, Eco 5: Udon noodle waste, Eco 6: Green tea waste, Con1: Calcium carbonate, Con2: Corn, Con3: Barley, Con 4: Soybean meal, Con5: Wheat bran, Rou1: Hay, Rou2: Rice straw

Table 5
Replacement prices of food by-products¹⁾ (yen²⁾/kg, as-fed basis)

Substitution rate of food by-products for concentrates Price level of concentrates ³⁾	Low (0.25)			Middle (0.50)			High (0.75)		
	Low	Average	High	Low	Average	High	Low	Average	High
N and P penalty ³⁾									
No penalty	19	23	28	15	17	21	10	13	18
Penalty x1	19	22	27	13	17	20	10	12	18
Penalty x2	16	21	26	12	16	20	10	12	18
Mean	18	22	27	13	17	20	10	12	18

¹⁾ Maximum price of food by-products when the feed cost with the use of food by-products is below the cost without the use of food by-products.

²⁾ 1 euro = 120 yen

³⁾ see Table 3

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1 **Fig. 1.** Outline of the system of feed formulation with food by-products in this study.

2
3 **Fig. 2.** Differences in total feed costs between the cases with and without food by-products under
4 three nitrogen and phosphorus penalty conditions under different prices of food by-products on an
5 as-fed basis.

6
7 **Fig. 3.** Differences in nitrogen and phosphorus excretions between the cases with and without the
8 use of food by-products, when the price of food by-products was set to be 16 (yen/kg, as-fed
9 basis).

10
11 **Fig. 4.** Effect of nitrogen and/or phosphorus penalty levels on feed costs with the use of food
12 by-products, when the price of food by-products was set to be 16 (yen/kg, as-fed basis).

13
14 **Fig. 5.** Effect of nitrogen and/or phosphorus penalty levels on the reduction rates of (a) nitrogen
15 and (b) phosphorus excretions in the production with the use of food by-products.

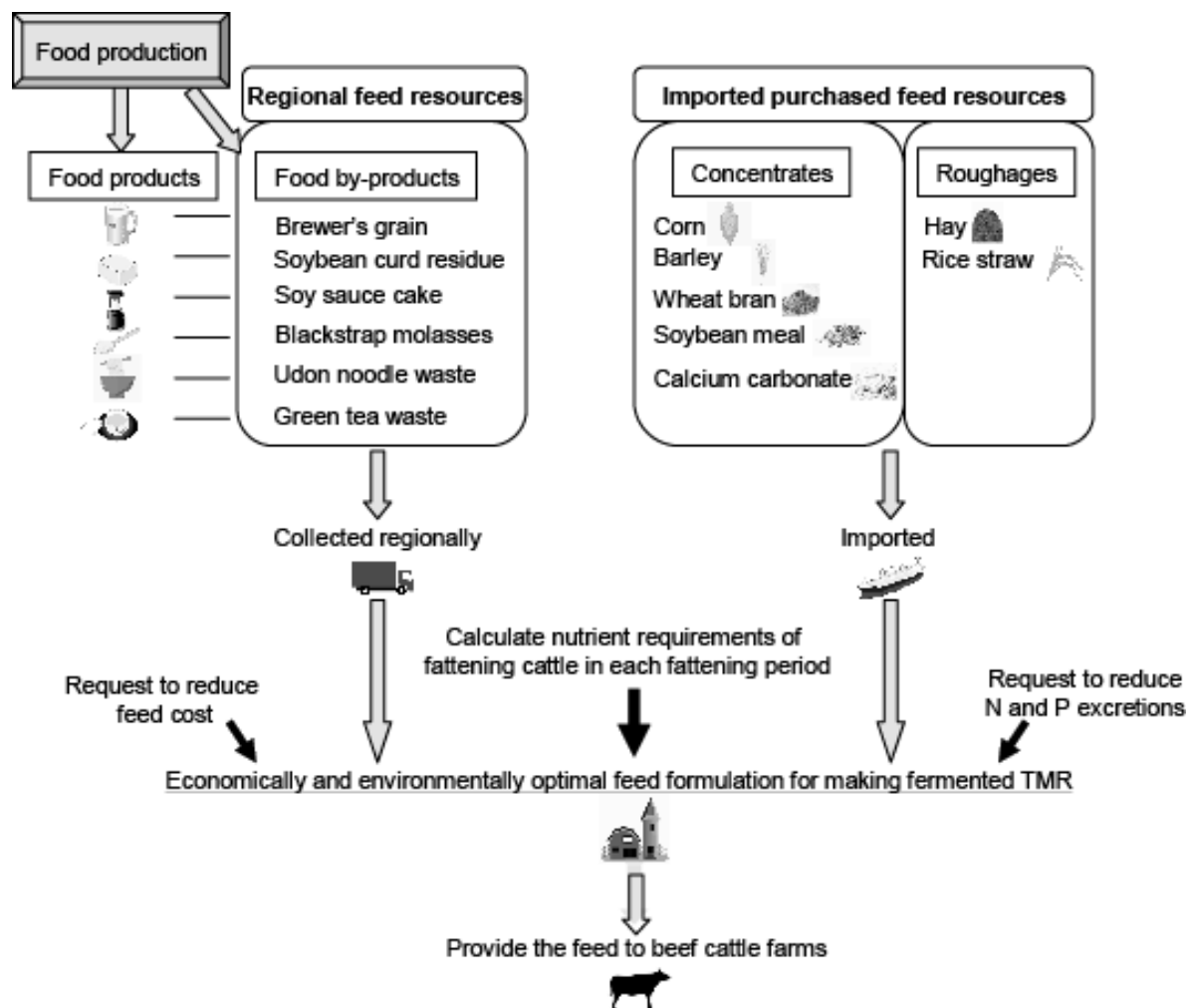


Fig. 1. Outline of the system of feed formulation with food by-products in this study

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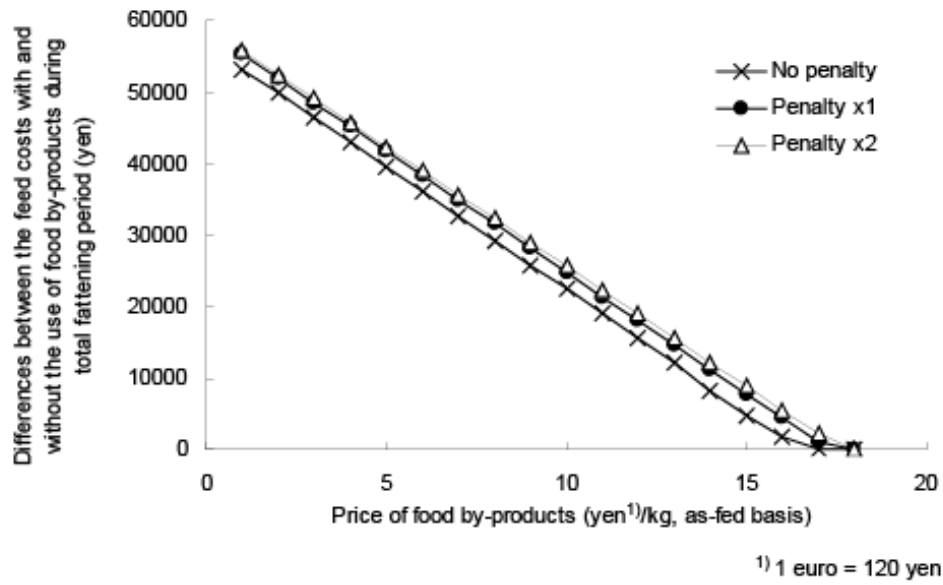


Fig. 2. Differences in total feed costs between the cases with and without food by-products under three nitrogen and phosphorus penalty conditions under different prices of food by-products on an as-fed basis.

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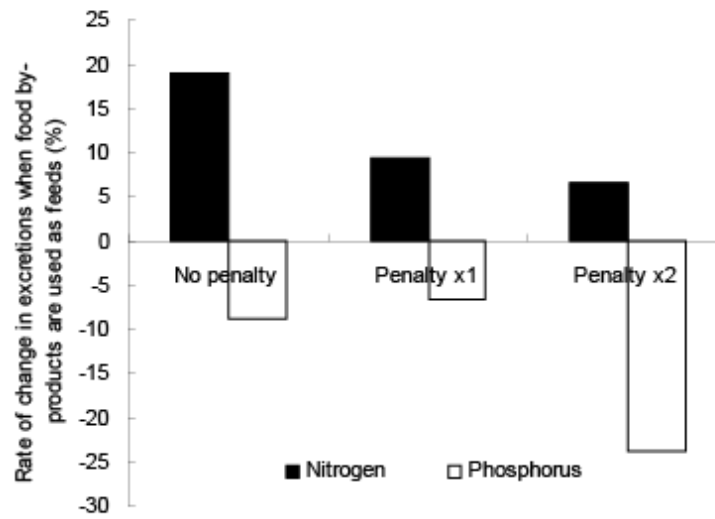


Fig. 3. Differences in nitrogen and phosphorus excretions between the cases with and without the use of food by-products , when the price of food by-products was set to be 16 (yen/kg, as-fed basis).

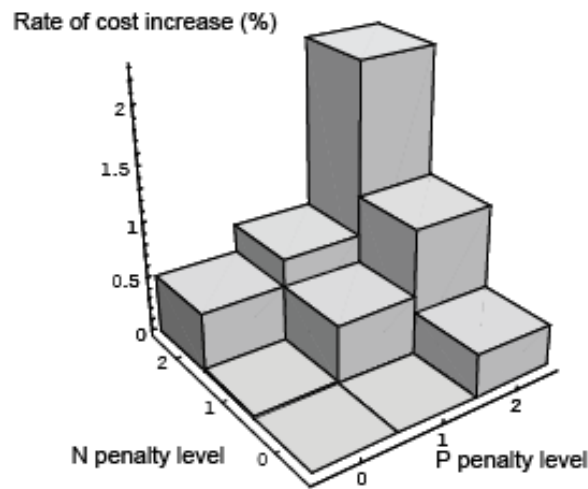


Fig. 4. Effect of nitrogen and/or phosphorus penalty levels on feed costs with the use of food by-products, when the price of food by-products was set to be 16 (yen/kg, as-fed basis).

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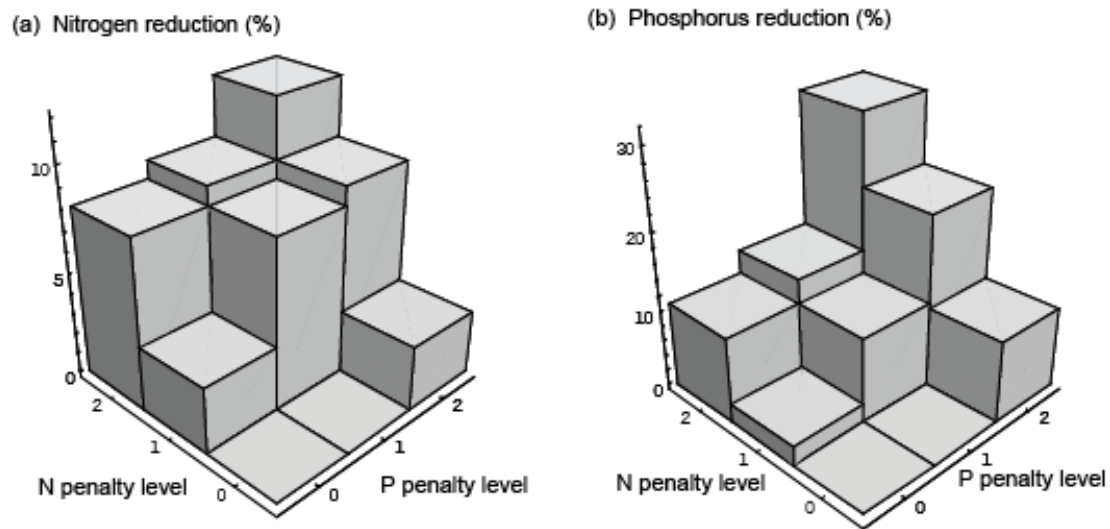


Fig. 5. Effect of nitrogen and/or phosphorus penalty levels on the reduction rates of (a) nitrogen and (b) phosphorus excretions in the production with the use of food by-products.

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